Low-ν Flux in NuMI

D. Naples

NuMI-X Meeting

April 25, 2014

Outline
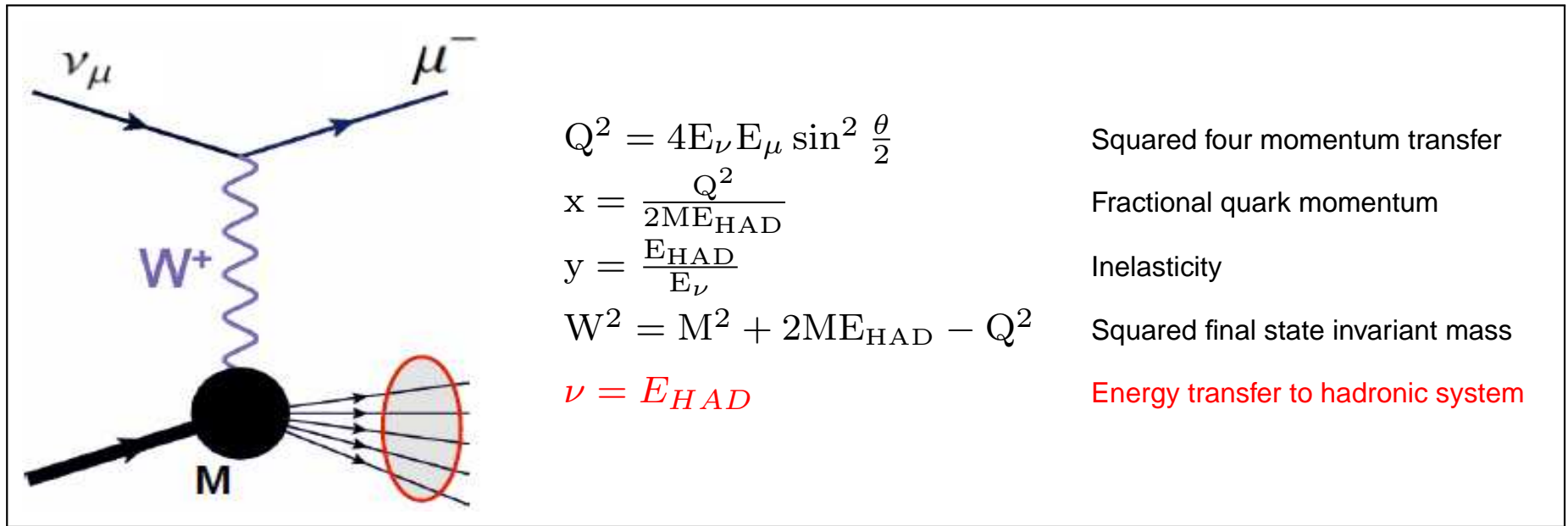
- Reminder of Low-ν Method

- Low-ν Flux Measurement from MINOS.

- Low-ν for beam fits.

- Part II- Ongoing work and plans for MINERνA

"Low-ν" Flux Method

Direct measurement of flux from a well-understood behavior of the cross section.

- Method originated in high energy neutrino scattering experiments CCFR, NuTeV.

  S. Mishra, Proceedings of the Workshop on Hadron Structure Functions and Parton Distributions, 1990 p.84 and W. G

  Seligman, PhD Thesis, Columbia Univ. (1997) Nevis 292.

  ▶ NuTeV and CCFR energy range (30-300) GeV

- Adapted to lower NuMI beam energies by MINOS (3-50 GeV). " Neutrino and Antineutrino

  Inclusive Charged-current Cross Section Measurements with the MINOS Near Detector.", by MINOS Collaboration (P.

  Adamson et al.), Phys. Rev. D 81, 072002 (2010) and D. Bhattarchya, PhD Thesis, Univ. of Pittsburgh (2009).

  ▶ MINOS ν flux (3-50 GeV); $\overline{\nu}$ flux (6-50 GeV).

- MINERνA is also applying this technique in NuMI (2-20 GeV).

  ▶ Finer granularity and better E_{HAD} resolution.

  ▶ $\overline{\nu}$ flux from RHC beam data.

"Low-ν" Flux Basic Idea

$$Q^2 = 4E_\nu E_\mu \sin^2 \tfrac{\theta}{2}$$ Squared four momentum transfer

$$x = \frac{Q^2}{2ME_{HAD}}$$ Fractional quark momentum

$$y = \frac{E_{HAD}}{E_\nu}$$ Inelasticity

$$W^2 = M^2 + 2ME_{HAD} - Q^2$$ Squared final state invariant mass

$$\nu = E_{HAD}$$ Energy transfer to hadronic system

- Use low-$\nu (= yE_\nu)$ behavior of the CC neutrino cross section.

  ▶ Differential cross section, $\frac{d\sigma^{\nu,\overline{\nu}}}{d\nu}$, is independent of energy in the limit $\nu \to 0$.

  ▶ Measures the shape of the flux with energy.

- Use external world cross section data to normalize to absolute flux.

  ▶ Total neutrino cross section at high energy ($E > 10$ GeV) is well known (few percent level).

Low-ν Flux Technique

Start with general expression for differential cross section:

$$\frac{d^2\sigma^{\nu,\overline{\nu}}}{dxd\nu} = \frac{G^2 M}{\pi}\left[\left(1 - \frac{\nu}{E} - \frac{Mx\nu}{2E^2} + \frac{\nu^2}{2E^2}\frac{1 + 2Mx/\nu}{1 + R}\right)F_2(x) \pm \frac{\nu}{E}\left(1 - \frac{\nu}{2E}\right)xF_3(x)\right]$$

Integrate over x for fixed ν:

$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right)$$

$$A = \frac{G^2 M}{\pi}\int F_2(x)dx$$

$$B = -\frac{G^2 M}{\pi}\int\left(F_2(x) \mp xF_3(x)\right)dx$$

$$C = B - \frac{G^2 M}{\pi}\int F_2(x)\left(\frac{1 + \frac{2Mx}{\nu}}{1 + R(x)} - \frac{Mx}{\nu} - 1\right)dx$$

- A, B and C can also be expressed as integrals over form factors, etc.

- At low y, (i.e. low ν and high E_ν) $\Rightarrow$ ($\frac{\nu}{E}$) and ($\frac{\nu}{E}$)^2 terms are small.

$$\frac{d\sigma}{d\nu}^{\nu}_{\lim\, y \to 0} = \frac{d\sigma}{d\nu}^{\overline{\nu}}_{\lim\, y \to 0} = A \qquad \textit{approaches a constant, independent of } E_\nu.$$

- Normalization procedure determines A; correction terms ($\frac{B}{A}$ and $\frac{C}{A}$) are computed from the cross section model.
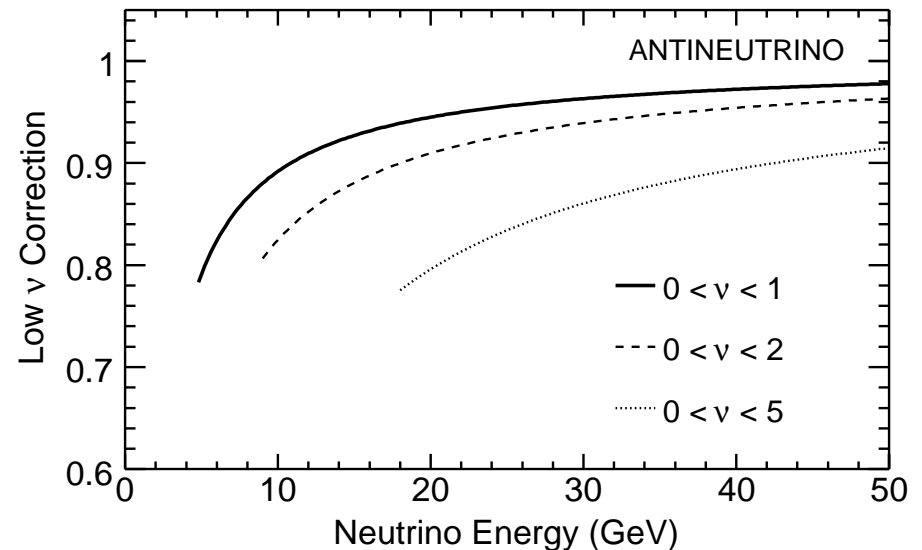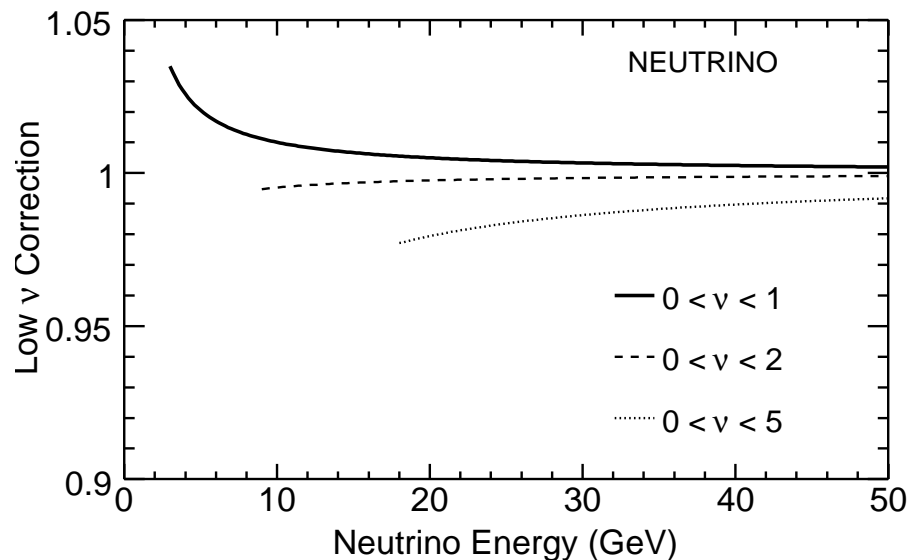
Low-ν Flux Technique (cont'd)

- Select a CC sample at low ν , $N(E)_{(\nu < \nu_o)}$

- Apply a correction for $\frac{\nu}{E}$ dependence, $S^{\nu,\overline{\nu}}(E)$.

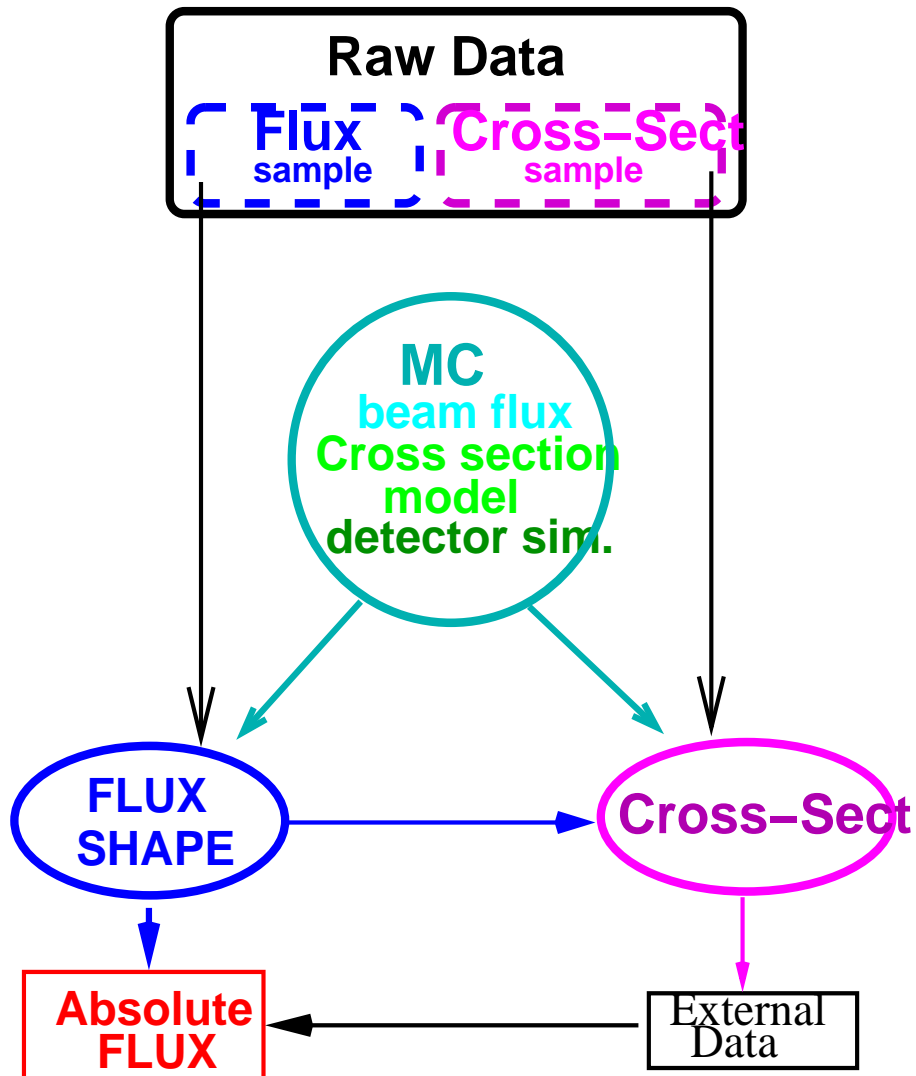$$\boxed{\Phi^{\nu,\overline{\nu}}(E) \propto \frac{N(E)_{(\nu < \nu_o)}}{S^{\nu,\overline{\nu}}(E)}} \quad \text{where} \quad \boxed{SS^{\nu,\overline{\nu}}(E) = \frac{\sigma(\nu < \nu_o, E)}{\sigma(\nu < \nu_o, E \to \infty)}}$$

- MINOS uses a sliding ν cut to improve sample statistical precision.

MINOS Low-ν Flux

$$\sigma_{CC}(E) = \frac{(N_{CC}(E) - B_{CC}(E)) \times A_{CC}(E)}{\Phi(E)}$$

$$\Phi(E) \propto \frac{(F(E) - B_\Phi(E)) \times A_\Phi(E)}{S(\nu_0, E)}$$

Raw Data

Flux sample   Cross–Sect sample

MC beam flux Cross section model detector sim.

FLUX SHAPE

Cross–Sect

Absolute FLUX

External Data

- Inclusive sample $N_{CC}(E)$

- Flux sample $F(E)$

- Data correction from MC

  - acceptance correction $A_{CC}(E)$ $A_\Phi(E)$

  - backgrounds correction $B_{CC}(E)$ $B_\Phi(E)$

- Model correction $S(\nu_0, E)$

- Flux is normalized using data >30 GeV which overlaps with precise high-energy measurements. $\sigma^\nu_{\text{world}}(30-50\text{GeV}) = 0.675 \pm 0.009 \times 10^{-38} \text{cm}^2/\text{GeV}$

▶ Antineutrino flux sample uses the same normalization.

MINOS Low-ν Flux (cont'd)

$(N(E)_{CC})$ Inclusive Sample

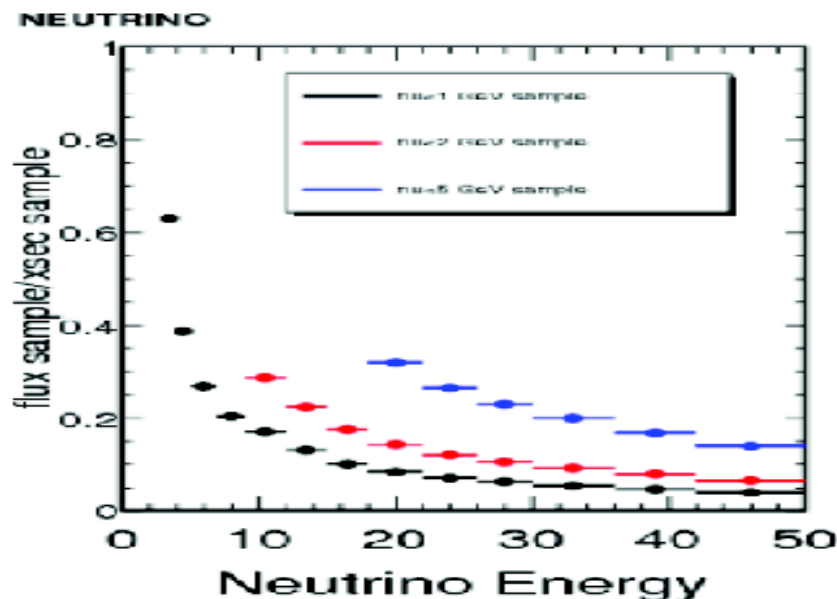- Fiducial events with 1 good track.

- $E_\mu > 1.5$ GeV (select CC)

- $E_\nu > 3$ GeV ν, $E_\nu > 5$ GeV $\bar{\nu}$ FHC.

- Additional charge-sign purity cuts for $\bar{\nu}$.

$(F(E))$ Flux Sample

- Subsample of CC inclusive sample.

- Sliding ν_o cut

  ▶ $\nu_0 = 1$ for $E_\nu < 9 GeV$

  ▶ $\nu_0 = 2$ for $9 < E_\nu < 18 GeV$

  ▶ $\nu_0 = 5$ for $E_\nu > 18 GeV$

Choice of ν cut depends on

- Hadronic energy resolution (bin purity)

- Trade off between statistical precision at high energy (normalization bin) and inclusive vs. flux sample overlap at low energy.

NEUTRINO

flux sample/xsec sample

Neutrino Energy

ANTINEUTRINO

flux sample/xsec sample

Neutrino Energy
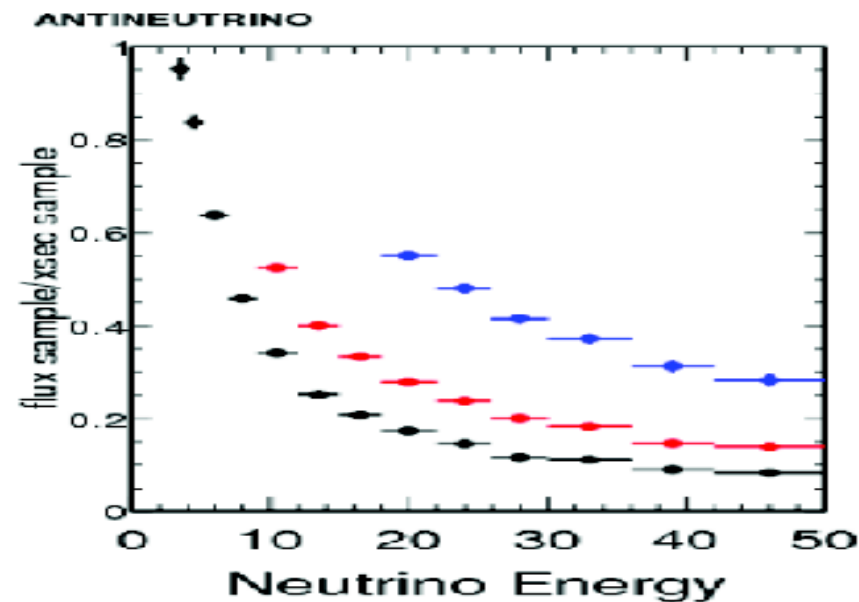
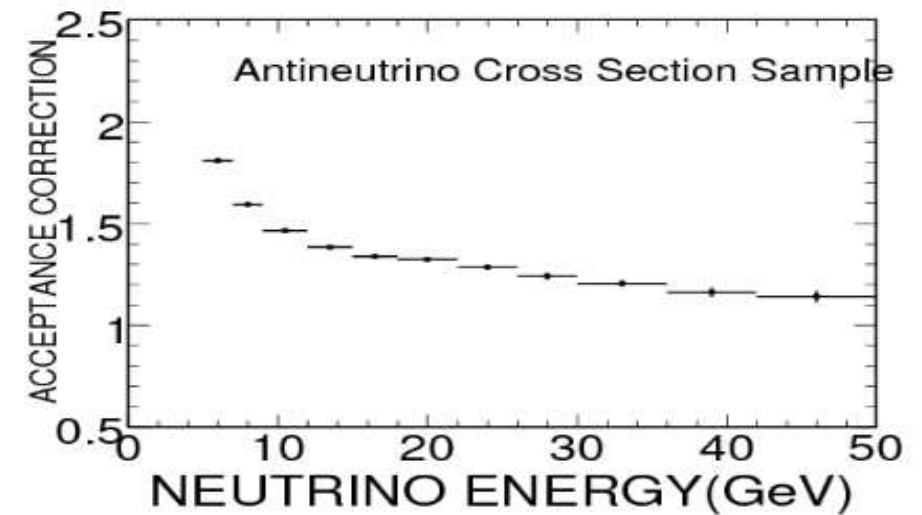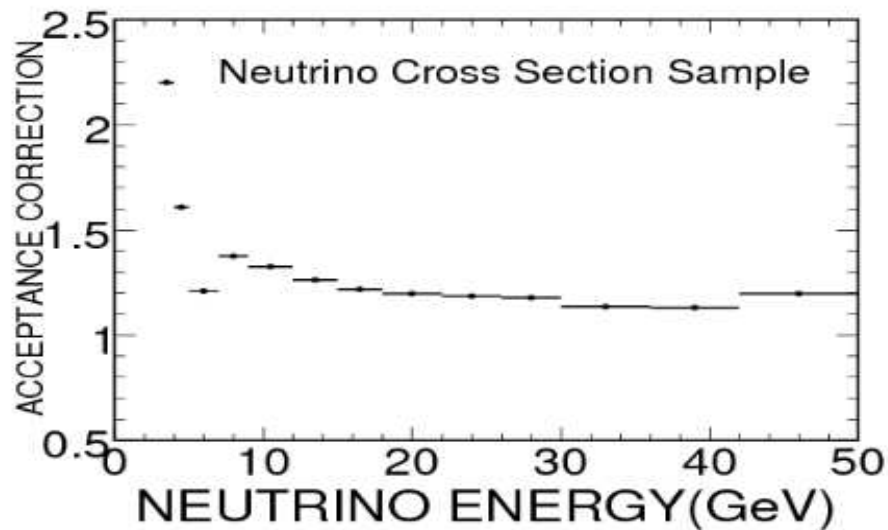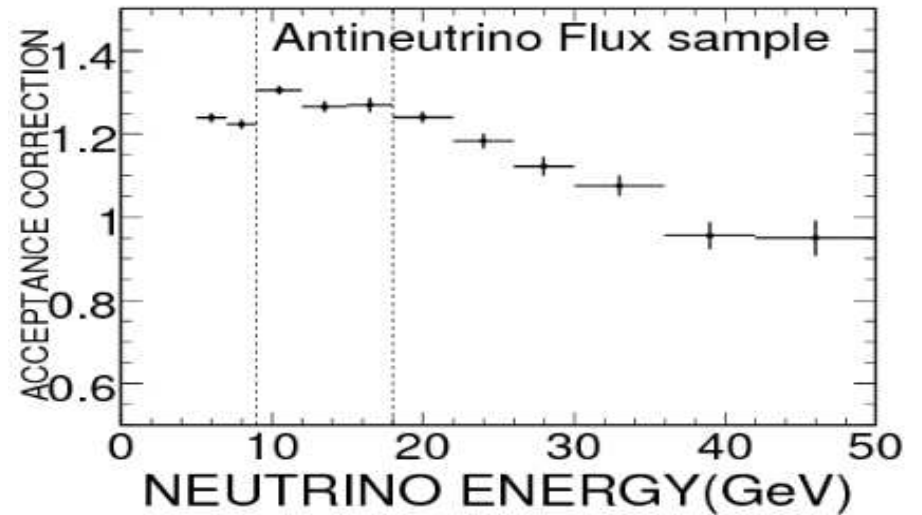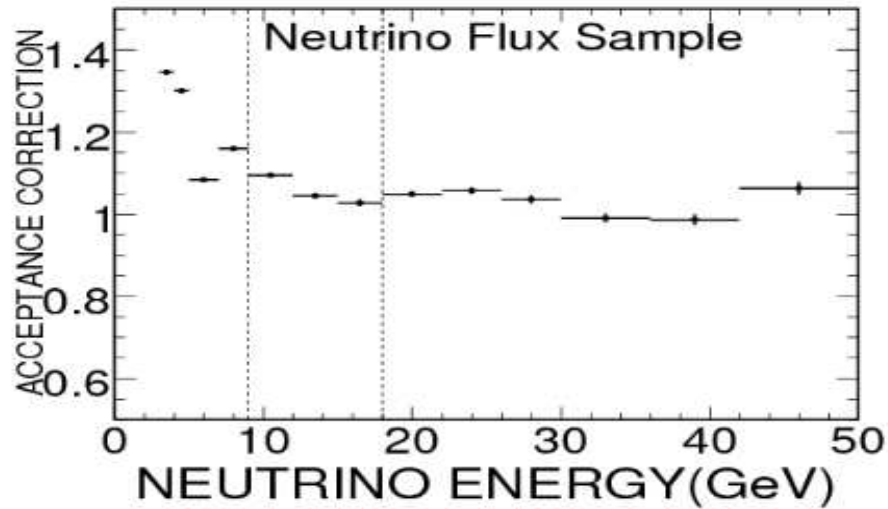# Acceptance Corrections Definition

Acceptance Correction (corrects for effects of event selection, smearing and detector geometry)

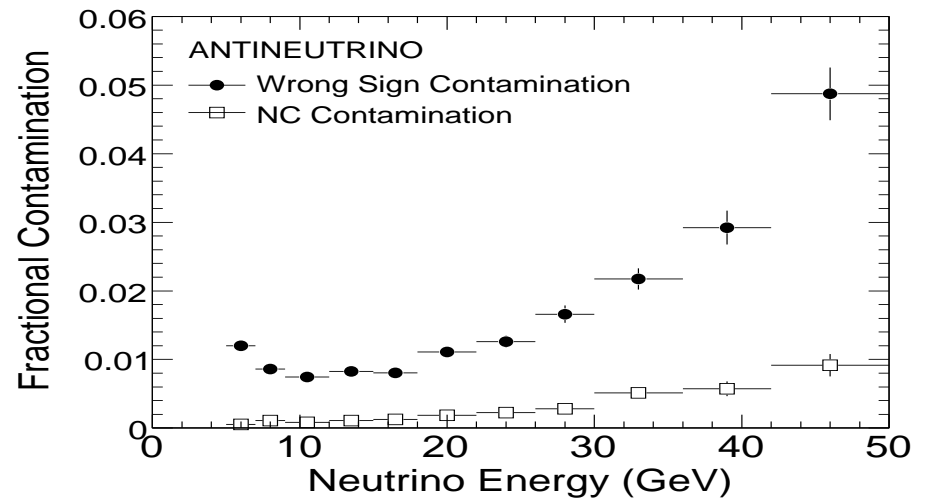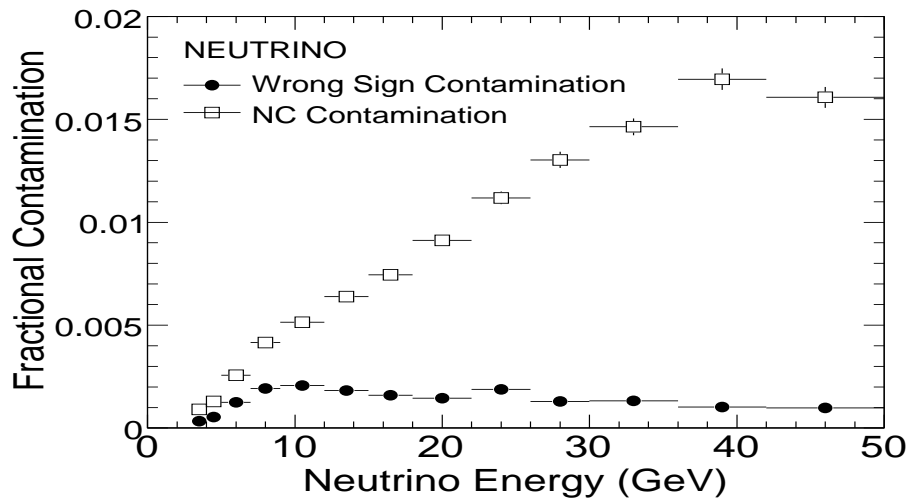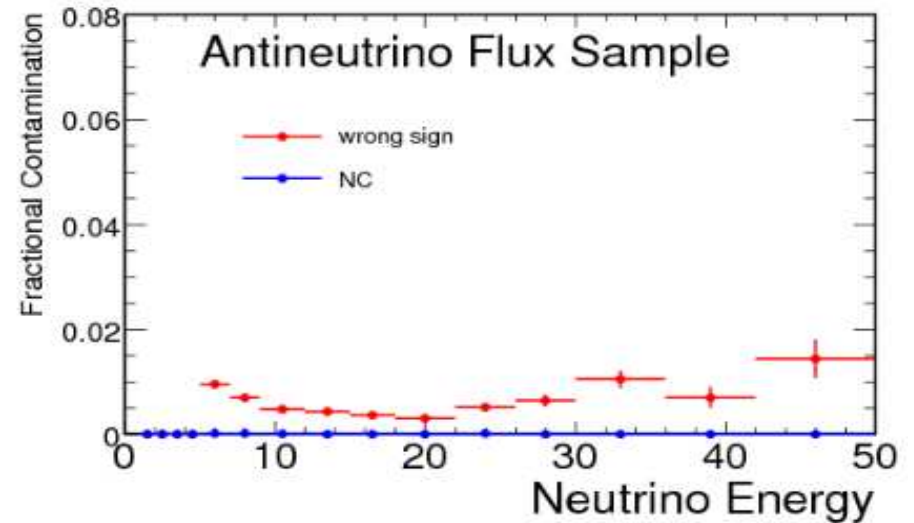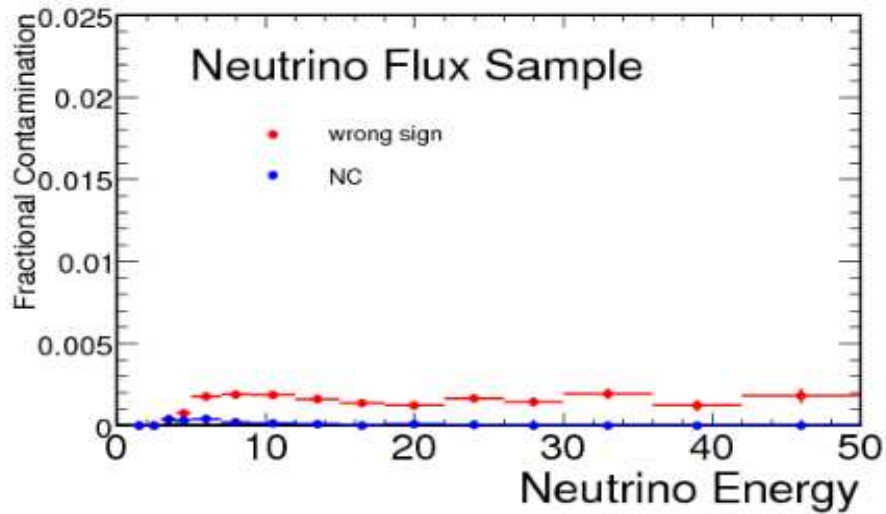$$Accep_{MC}(E) = \frac{N^{MC}_{TRUTH}(E)}{N^{MC}_{RECO}(E)}$$

Neutrino

reciprocal of Acceptance correction vs Neutrino Energy

Legend:
- total neutrino sample
- stopping upstream
- stopping downstream
- exiting upstream
- exiting downstream
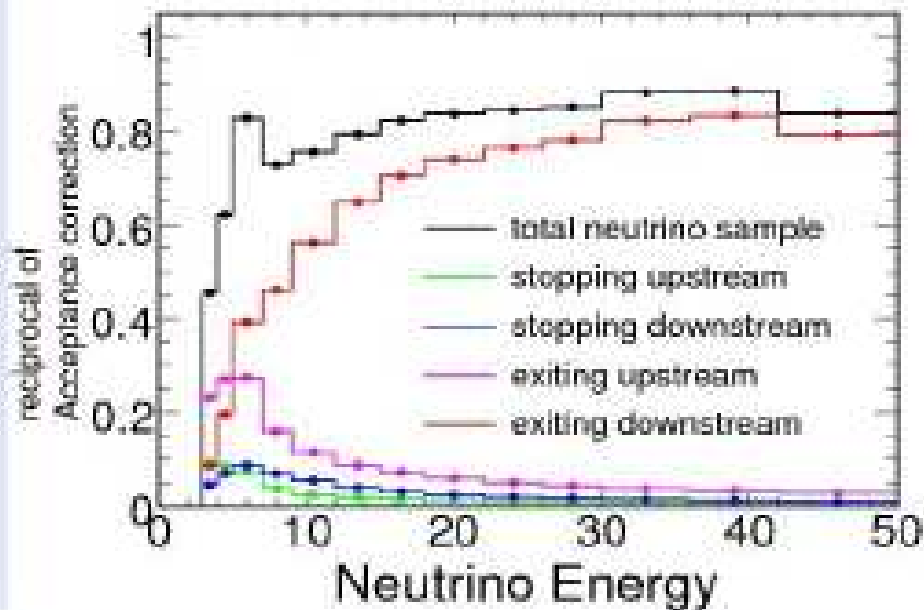
Acceptance Corrections (A_{CC}, A_Φ)

Wrong-sign and NC Backgrounds

MINOS Low-ν Flux

E bin	ν Flux	Error	$\bar{\nu}$ Flux	Error
(GeV)	Particles/GeV/m^2/10^9 PoT			
3-4	8.05×10^4	5.2×10^3	-	-
4-5	3.06×10^4	2.4×10^3	-	-
5-7	9.07×10^3	5.3×10^2	2.80×10^3	330
7-9	5.18×10^3	3.5×10^2	2.32×10^3	170
9-12	3.21×10^3	2.2×10^2	1.32×10^3	85
12-15	1.94×10^3	1.0×10^2	6.89×10^2	42
15-18	1.09×10^3	65	3.79×10^2	24
18-22	629	37	190	14
22-26	348	20	86.3	7.8
26-30	200	13	40.1	3.9
30-36	119	6.8	19.3	1.9
36-42	72.2	3.9	9.6	0.9
42-50	51.6	2.8	4.9	0.5
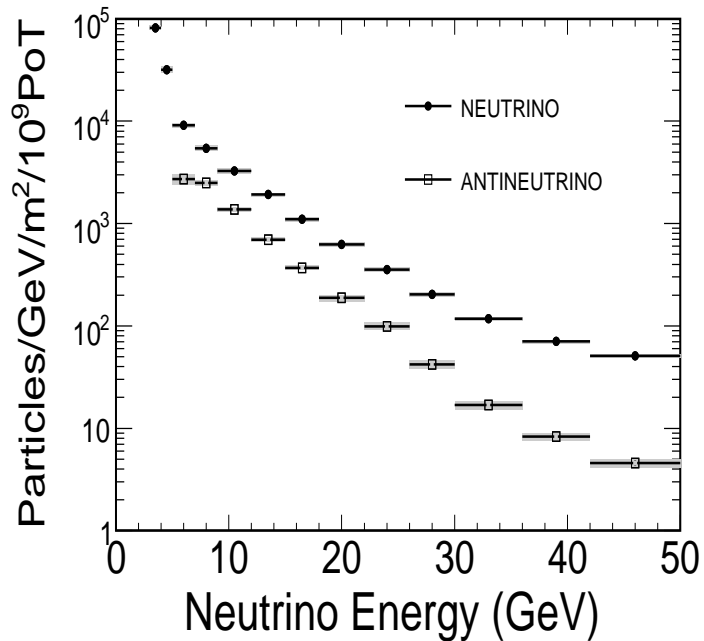
- Data from Runs 1&2 (2.45E20 PoT) of MINOS.
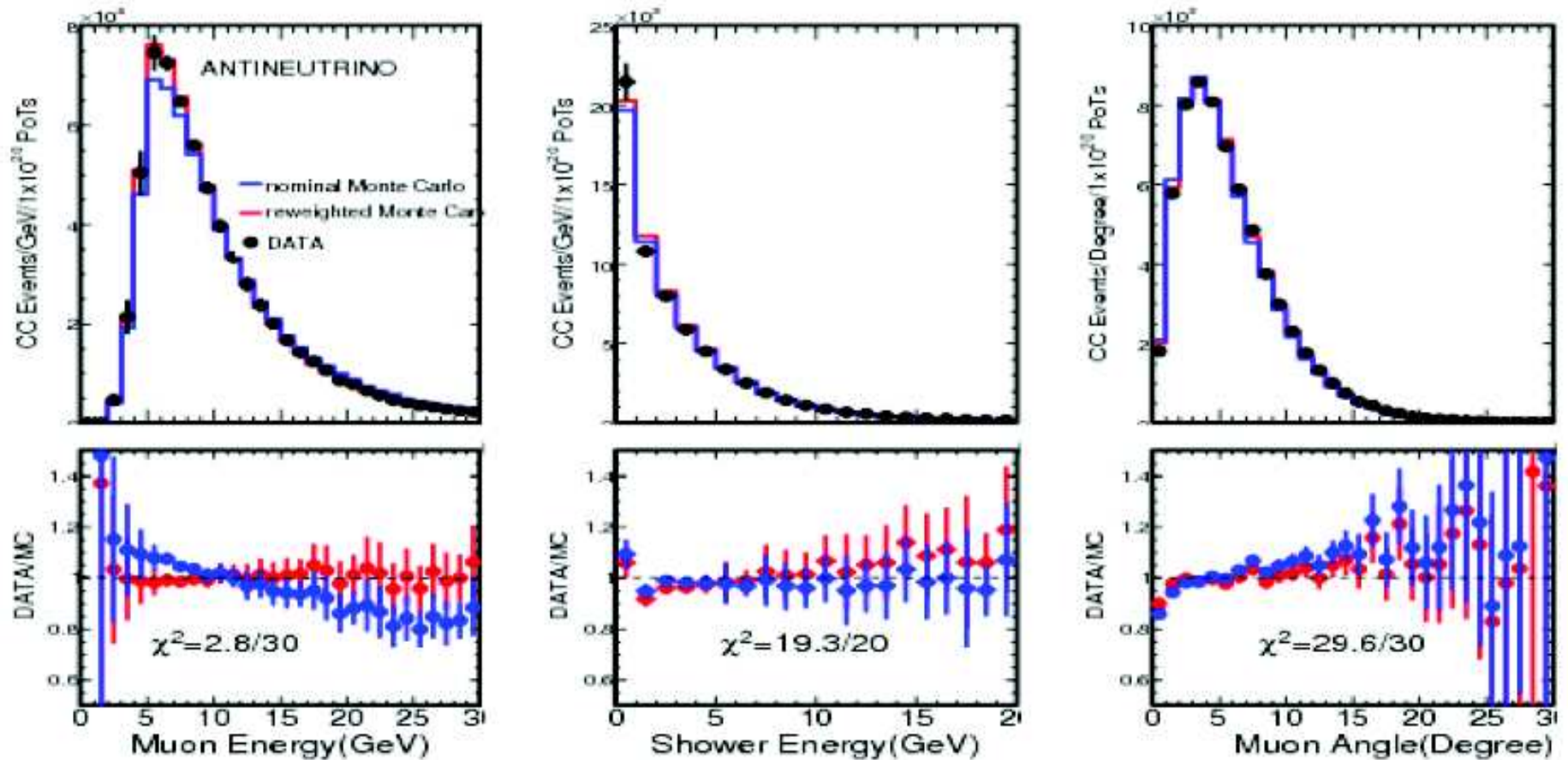
- Low-ν flux compares well with SKZP-tuned flux.

" Neutrino and Antineutrino Inclusive Charged-current Cross Section Measurements with the MINOS Near Detector.", by MINOS Collaboration (P. Adamson et al.), Phys. Rev. D 81, 072002 (2010) and D. Bhattarchya, PhD Thesis, Univ. of Pittsburgh (2009).

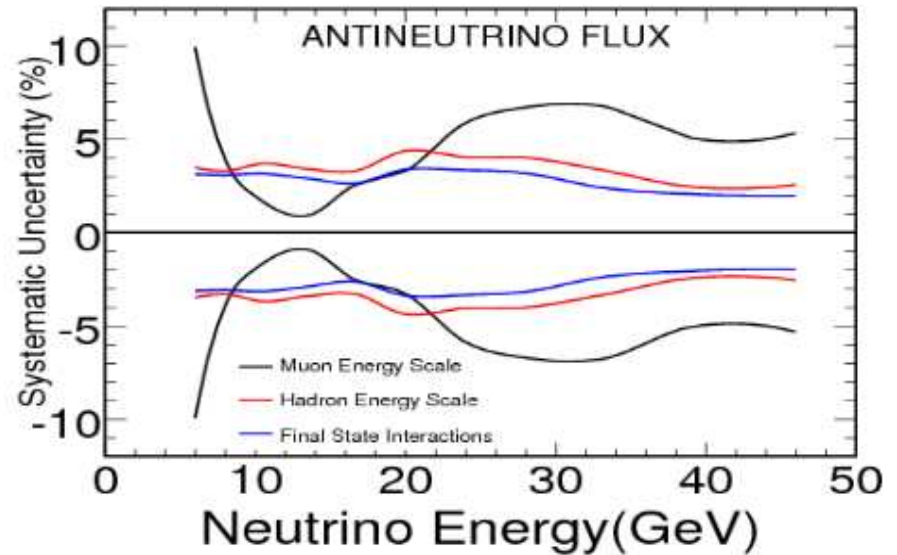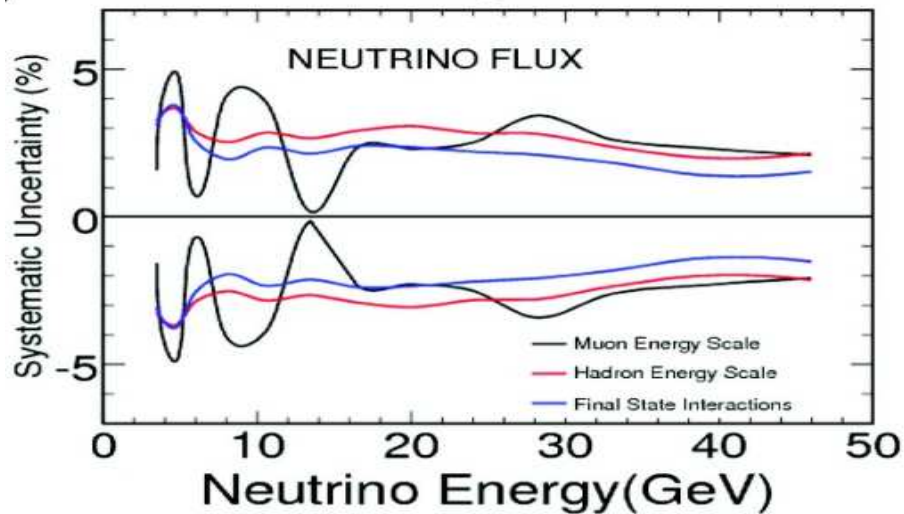# Reweighted MC Comparisons

- Low-ν flux weights applied.
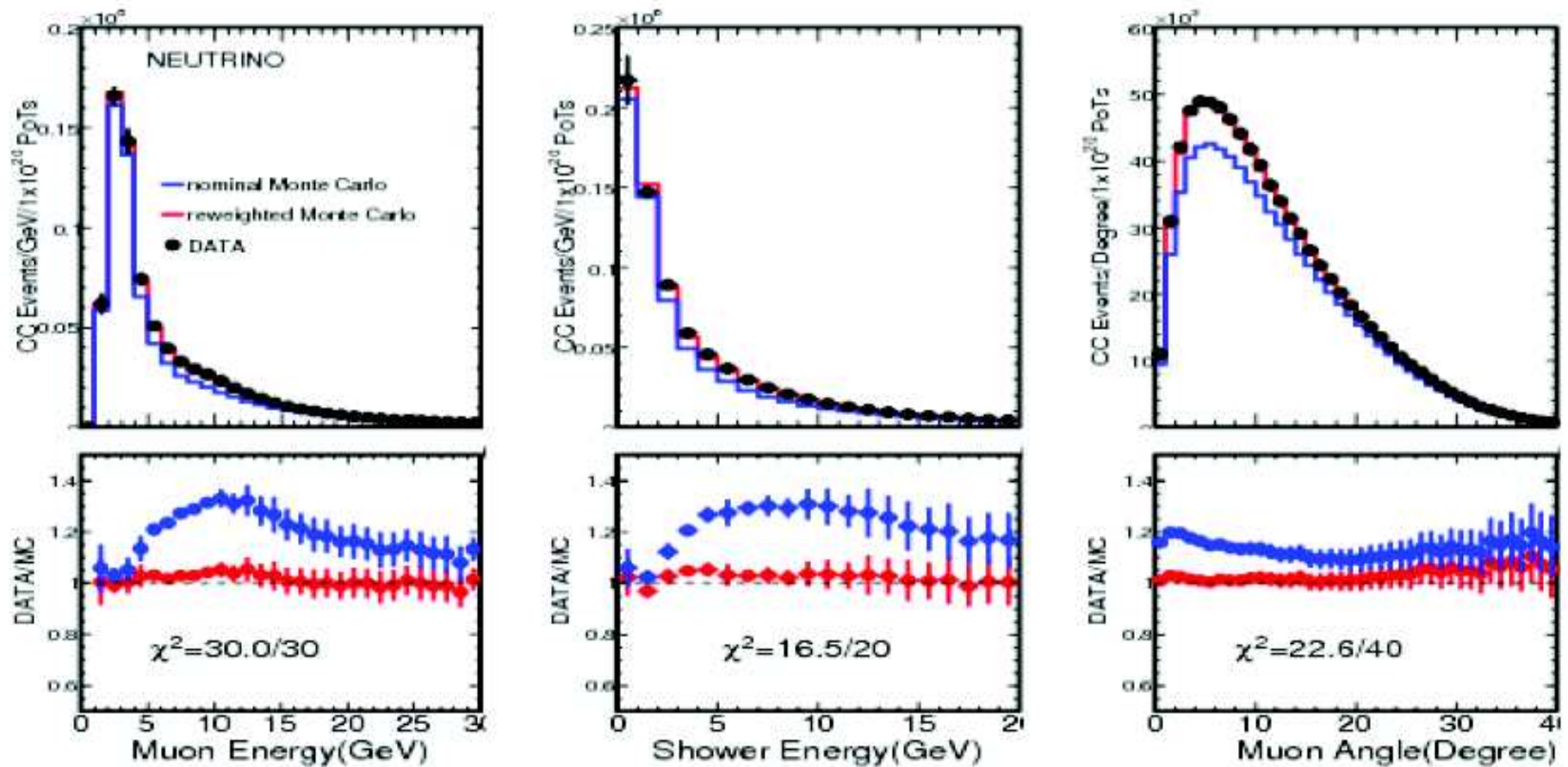
Reweighted MC Comparisons (cont'd)

Flux Precision

- Low-ν flux compares well with SKZP-tuned flux but has substantially smaller error bars.

MINOS Collaboration, Phys. Rev. D 81, 072002. D. Bhattacharya's PhD thesis

- Results are systematics dominated below $\sim$15 GeV.

- **Muon energy scale 2% range, 4% curvature**

- **Hadronic energy scale 5.6%**

- **Intranuclear final state rescattering model (UPDATE Improved treatment in GENIE).**

- **Contamination ($\overline{\nu}$ sample only)**

- **Acceptance and smearing correction modeling (Rev. field running)**

- **Cross section modeling, (BY parameters, MA QE, etc.)**

Flux Precision (cont'd)

- Compare with current MINERνA flux error band.

Current Flux Uncertainties

MINOS Collaboration, Phys. Rev. D 81, 072002. D. Bhattacharya's PhD thesis
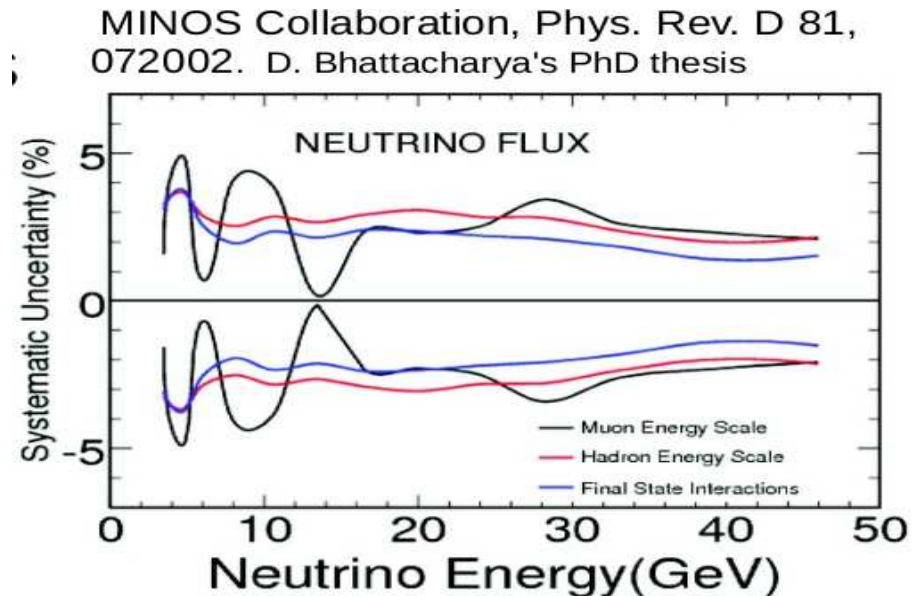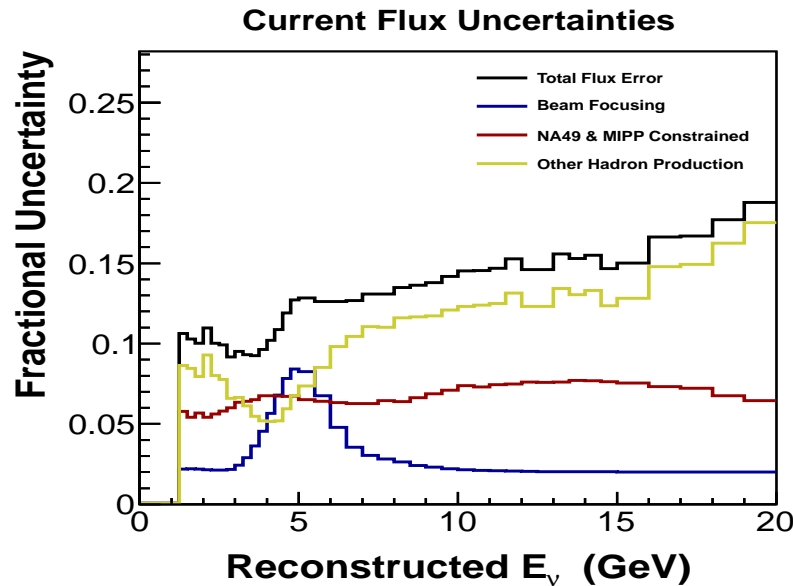
Original motivation for Low-ν flux was for total cross section measurement.

- Low-ν flux used directly in cross section measurements has substantailly smaller error bars.

  ▶ Caveat: Sample overlap must be considered if used in cross section measurements.

- Errors band above 15 GeV ($\sim$10%) can be reduced (statistics dominated).

Low-ν Flux in Beam Fits

- MINERνA is using low-ν flux for beam tuning (L. Ailaga and M. Korodosky).

  ▶ Using direct flux measurement instead of event rate reduces sensitivity to detector and cross section parameters in fit.

    ▷ Limited cross section model parameter dependence (to those that change the shape with energy at low-ν).

    ▷ Less dependence on hadronic energy scale than CC-inclusive samples.

    ▷ (More dependence on muon energy scale).

Low-ν Flux in ME Beam

This method works at least as well and argueably better at higher energies.

- Increased sample statistics in normalization region.

- Model correction decreases as E_ν increases (large for $\overline{\nu}$ at low energies).

- Other systematic errors are perhaps also smaller (hadronic final state effects are fractionally smaller at higher energies).

MINOS/MINOS+ complementary to MINERνA for low-ν flux.

- MINOS has better shower containment and a lower muon energy threshold.

- MINERνA has better hadron shower resolution (better for lower energies).

How low can you go?

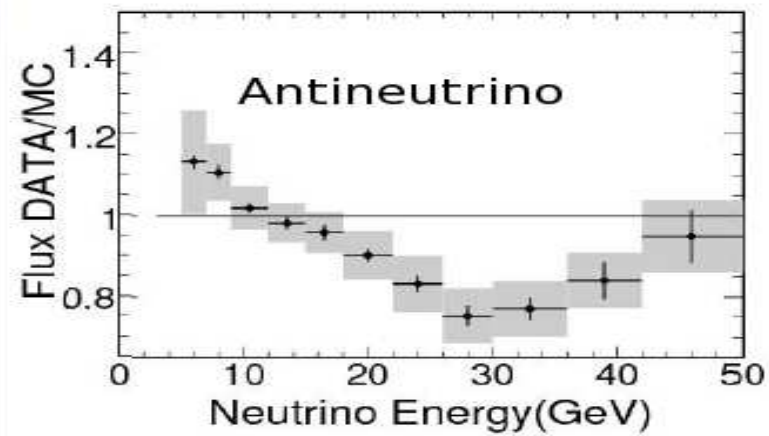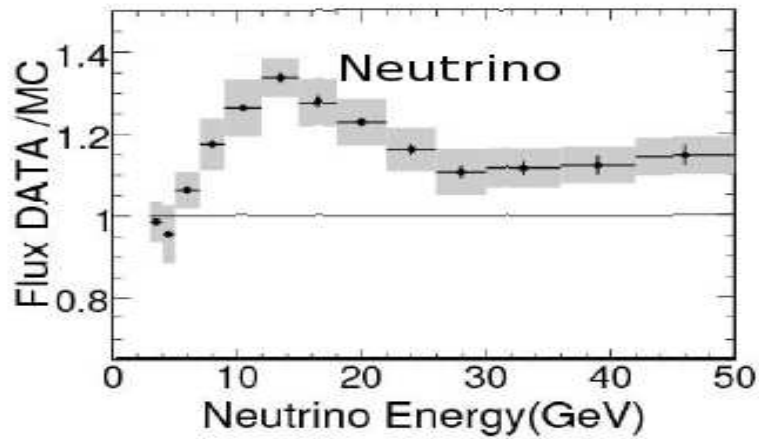Part II - ongoing work in MINERνA to push to lower energies and better systematic precision.

Issues

- Model uncertainties at lower energies.

- Detector shower energy resolution (lower ν-cut and bin purity).

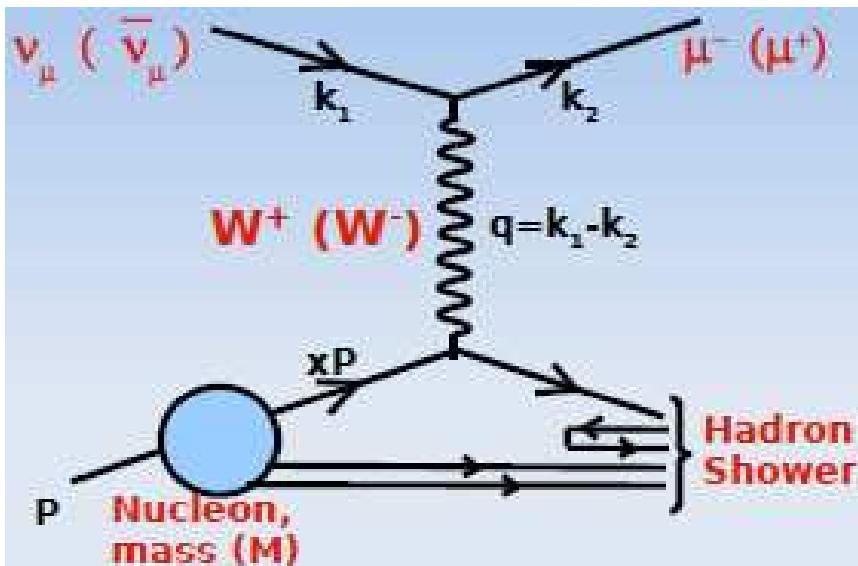- Sample overlap (important for cross section measurements).

- ...

Extra

Reweighted MC Comparisons

Flux reweighting factor

Neutrino Scattering

ν_μ $(\bar{\nu}_\mu)$

k_1

k_2

μ^- (μ^+)

W^+ (W^-) $q = k_1 - k_2$

xP

Hadron
Shower

P Nucleon,
mass (M)

Measured Quantities :

P_μ, θ_μ, E_{HAD}

| Invariant quantities		Lab Frame
$\nu = \dfrac{p.q}{M}$	(energy transfer to the hadronic system)	$\nu = E_{HAD}$
$y = \dfrac{p.q}{p.k_1}$	(inelasticity)	$y = \dfrac{E_{HAD}}{E_\nu}$
$Q^2 = -q^2$	(negative squared 4 momentum)	$Q^2 = 2 E_\nu E_\mu (1 - \cos\theta_\mu)$
$x = \dfrac{Q^2}{2\,p.q}$	(Bjorken Scaling variable)	$x = \dfrac{2 E_\nu E_\mu (1 - \cos\theta_\mu)}{2 M E_{HAD}}$

MINOS Cross Section Result
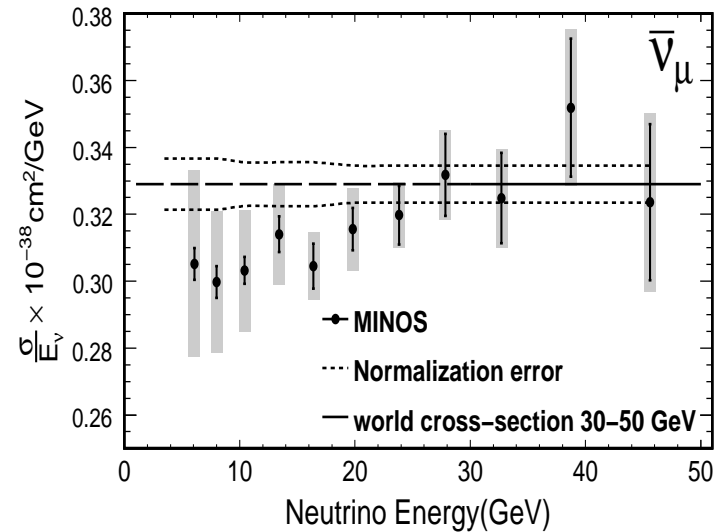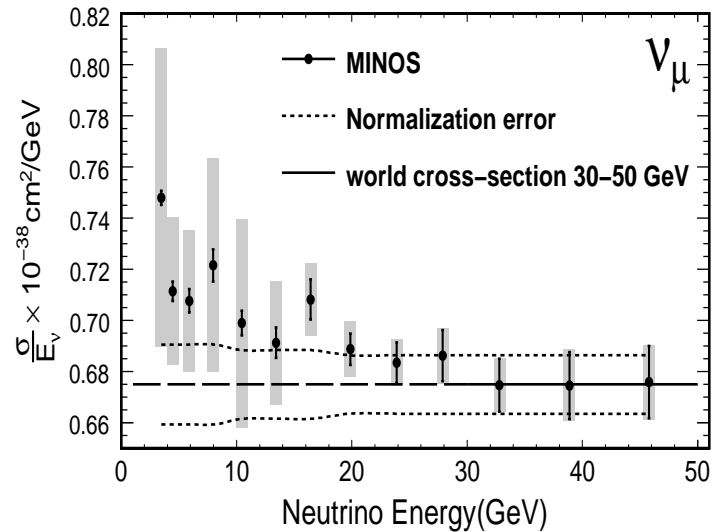
- Results are systematics dominated below ~15 GeV.

  - **Muon energy scale 2% range, 4% curvature**

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  - **Intranuclear final state rescattering model**

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MINOS Total Cross Sections
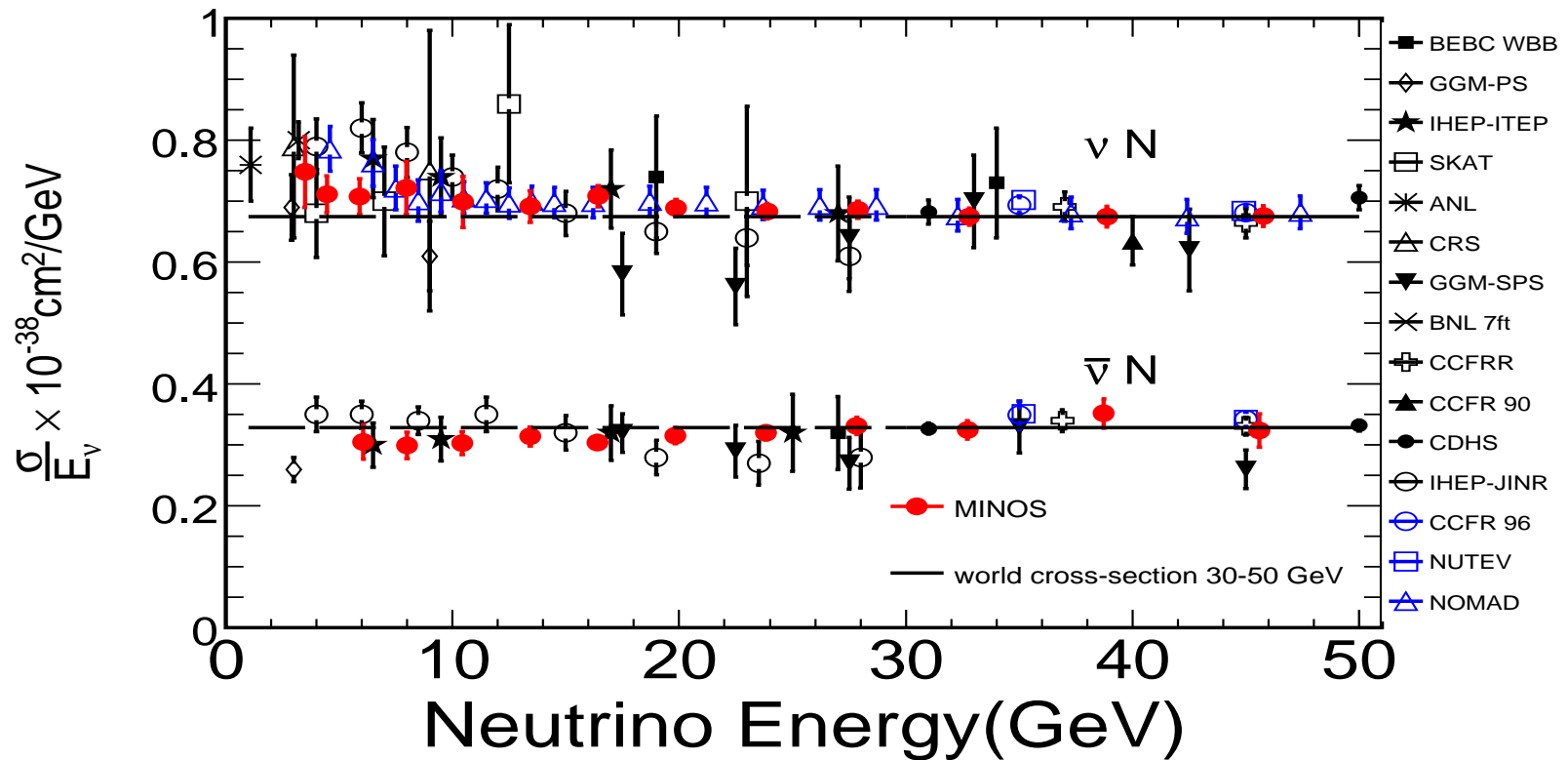
- | Neutrino cross section | MINOS result 2-8% precision in the $E < 30$GeV range.

- | Antineutrino cross section | MINOS result 3-9% precision in the $E < 30$GeV range.

- The cross section sample and the flux are measured in the same detector $\rightarrow$ some cancellation of systematic errors occurs in flux and cross section samples reducing the total systematic error.